ITEA Journal 2009; 30: 237–250

A Vision for the Future of Aeronautical Ground Testing

Edward M. Kraft, Ph.D., and Colonel Arthur F. Huber, II

Ground-based infrastructure consisting of wind tunnels and propulsion system test cells has been the predominant tool for the development of aeronautical systems since the Wright Brothers. With advances in modeling and simulation, as well as a reduced tempo for developing new major flight systems, it is reasonable to ask whether these aeronautical ground-test facilities will be needed in the future. The authors project that for the foreseeable future aeronautical systems, although more advanced than today, will still be the major mode for domestic and global transportation as well as for the transport of materiel and delivery of kinetic and nonkinetic effects for the military. Ground- and flight-test facilities will remain the primary sources of information on performance, operability, and durability for the development and sustainment of aeronautical systems.

A transformation in the design and use of aeronautical ground-test facilities will be required to maintain their viability as tools in the development of future applications. Through a confluence of design of experiments application, as well as advances in modeling and simulation, data systems, test techniques, flow diagnostics, and networking, there are emerging concepts that can dramatically reduce the overall cycle time for development of aeronautical systems. This article highlights these emerging technologies and creates a vision of how ground-test facilities can be used in the future to dramatically reduce development cycle time. The considerations that need to be addressed in the design of a future wind tunnel to optimize development cycle time are also explored.

Key words: Aeronautical ground-based test facilities; infrastructure; wind tunnels; propulsion test cells; workforce expertise; aircraft; modeling and simulation; future vision.

The Arnold Engineering Development Center (AEDC) is the Department of Defense's (DoD) premier center for ground-based research, development, test, and evaluation (RDT&E) of aeronautical and space systems. AEDC's infrastructure encompasses 58 test units, including subsonic, transonic, supersonic, and hypersonic wind tunnels; turbine engine altitude and sea-level test cells; rocket engine altitude test cells; space system vacuum chambers; arc-heated high-enthalpy materials test facilities; and aeroballistic impact ranges. Of these facilities, 28 are unique in the United States and 14 are considered unique in the world. Not all are now in service because several have been put into mothball status.

Today, fewer (but more complex and expensive) weapon systems rely on these test facilities for development. With this reduced demand come several perennial questions: What is the future for these facilities? Will they be replaced by modeling and simulation (M&S)? What existing or new test facilities will be needed in the future? How do we justify maintenance and operating budgets for lightly used, but critical facilities? Can we or should we offset costs by finding alternative uses and customer bases for these facilities?

In this article, we summarize the evolution of the ground-test capabilities we have today, the immediate challenges facing the national infrastructure, and the changes necessary to meet the future needs of the aeronautical community. *In the process we will shift the question from how do we justify the costs of sustaining these facilities to how do we transform them to reduce the cost and time required to field future weapon systems?* When viewed from the enterprise perspective of the overall weapon system development process, the effectiveness of test capabilities to increase the tempo of the acquisition process is more important than the cost efficiency of the test capabilities themselves. Focusing on tempo provides more value to the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **A Vision for the Future of Aeronautical Ground Testing**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Arnold Engineering Development Center (AEDC),100 Kindel Drive,Arnold AFB,TN,37389**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

acquisition enterprise than concentrating on operating costs. Such a perspective makes clearer the rationale for advancing the state of the art of ground-test facilities.

A brief history of ground-test facilities

Aeronautical ground-test facilities such as wind tunnels and propulsion test cells have been an integral part of the development of flight systems since the Wright Brothers. Although advances in test facilities paralleled early advances in the flight sciences leading up to World War II (Hansen, 1992), the modern era of ground-test facilities in the United States was initiated with the Unitary Wind Tunnel Act of 1949. This Act declared that the NASA Administrator and the Secretary of Defense should jointly develop a plan for construction "of wind tunnel facilities for the solution of research, development and evaluation problems in aeronautics," and to "revise the uncompleted portion of the unitary plan from time to time to accord with changes in national defense and scientific and technical advances." The Unitary Wind Tunnel Act provided the legislative drive to build the major wind tunnels at AEDC and NASA in the 1950s. Unfortunately, the Unitary Wind Tunnel Act has not been upgraded "to accord with changes" since 1958. A history of the early impact of the Unitary Wind Tunnel Act is given in Launias, Irvine, and Arrington (2002).

The technical vision for post-World War II aerospace test facilities was derived from the profound work of Theodore von Kármán and his colleagues (1945). Their thoughts were captured in the seminal work *Towards New Horizons*, which set the visionary path for the U.S. Air Force for the past 50 years. This study was chartered by Gen H. H. "Hap" Arnold who recognized that the United States was technologically far behind the Germans and the Japanese. After studying the advances made by our WWII adversaries, Von Kármán proposed in 1945 a far-reaching range of warfighting systems and the facilities required to achieve them. Promoting future concepts, Von Kármán said that "supersonic wind tunnels of large test sections are necessary so that not only the components, such as wing and fuselage, but whole airplanes as well can be studied for optimum design." This vision for advanced supersonic test facilities was documented 2 years before Chuck Yeager broke the sound barrier.

Authorization for the U.S. Air Force Secretary to develop an Air Engineering Development Center to support implementation of the Unitary Wind Tunnel Act was provided by U.S. Code Title 50, Section 521. The Air Engineering Development Center was dedicated by President Harry Truman as the Arnold Engineering Development Center on June 25, 1951, in honor of General Arnold. That a vision of such far-reaching scope and ramifications went from studies to reality in less than six short years is truly remarkable. That it occurred after the major drawdown following World War II and in the midst of the Korean War makes it even more noteworthy.

Vision push versus market pull for test facilities

Fortunately for the U.S. aeronautics community, the majority of ground-test facilities in use today were developed, erected, and commissioned to support the vision of General Arnold and Dr. von Kármán for technologically superior systems. "Further, faster, higher" was the mantra of the day. Without the drive and clairvoyance of that vision, many of the facilities we rely on today would never have been built. Capabilities were being developed to push the envelope and assure that the Air Force was technologically superior to all adversaries, not as a response to satisfy specific program requirements.

The history of the development of the major test facilities at AEDC, shown in *Figure 1*, demonstrates the significance of the early *vision-driven* approach to test facilities. Development of complementary wind tunnels within NASA follows a similar timeline. Although it was not always clear exactly what future systems would require of these test capabilities, 47 facilities were commissioned at AEDC in the 1950s and 1960s. A number of these were research facilities that have not survived until today. It is remarkable that designs for facilities like the world's largest supersonic propulsion wind tunnel following Von Kármán's vision were initiated in 1947.

After the 1970s, only a few facilities have been developed and generally had to be justified in support of specific programs. The timelines in *Figure 1* illustrate the lead times required to design, develop, and commission major test facilities. The timelines from concept to commissioning have become longer than in the 1950s and 1960s and are now of the same order as the timeline for developing new flight systems. In today's environment, unless major facilities are developed in anticipation of new requirements, they will generally be late to address needs and consequently are unlikely to be built.

State of current ground-test facilities

As is the case for AEDC, most wind tunnels in the rest of the United States used to develop flight systems were commissioned prior to 1970. The timelines for a number of major wind tunnels in the United States and Europe are shown in *Figure 2*. A number of U.S. wind tunnels, particularly in the commercial sector, have been decommissioned over time. A new U.S. National

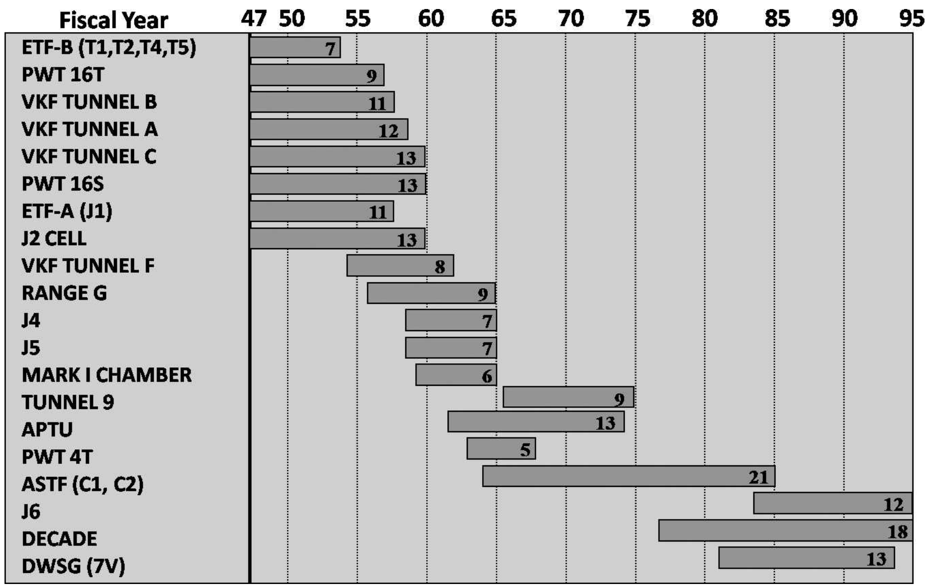

Figure 1. Historical development of test facilities at AEDC.

Wind Tunnel Complex was proposed in the mid-1990s but was never funded (Davis, Stamper, and Wiggum 1996). One can also see from *Figure 3* that European governments have been much more forward thinking in the recent era with respect to funding wind tunnel facilities. The trend over the last 20 years of increased European capture of aircraft market share is attributable at least in part to their investments in newer test capabilities.

Generally, U.S. wind tunnels that have survived until today range from 30 to 60 years in age. Over the next 25 years some of these tunnels will be approaching 50 to 80 years old. Also a number of the facilities built in the 1950s and 1960s were not designed for energy efficiency but for technical performance. Although service life extension programs and persistent upgrades to controls, instrumentation, and data systems will keep these tunnels viable for years to come, their inherent designs make them less efficient and effective in meeting future needs.

Turbine engine test cells are in a similar state. Over the past 20 years, through industry reductions and base realignments and closures, most ground testing of turbine engines in the United States is now done at AEDC. The Aerospace Systems Test Facility, which was commissioned in 1985, is the last major new

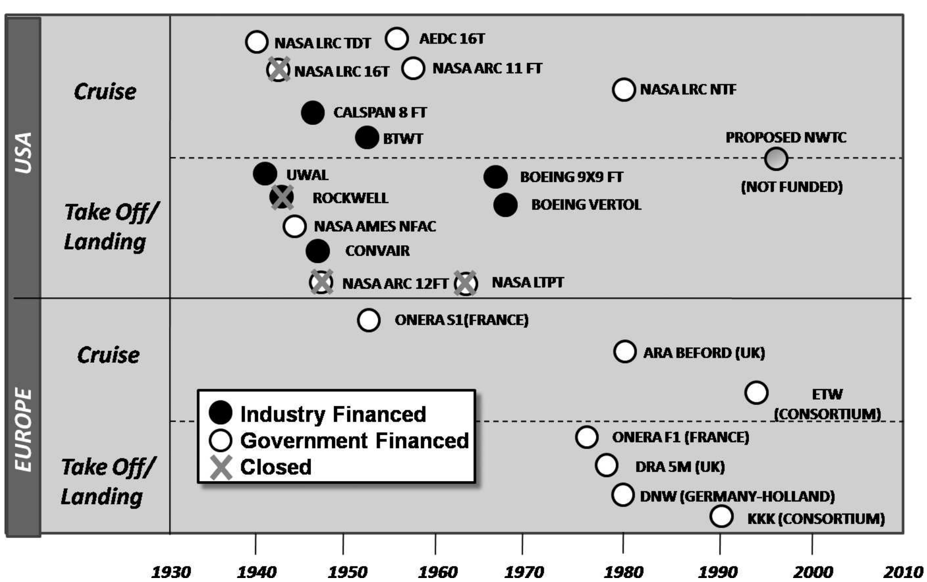

Figure 2. Timelines for major wind tunnels in the United States and Europe.

turbine altitude test capability built in this country, and it remains the premier facility of its type in the world. Following the 1995 base realignments and closure of the Navy's test facilities at Trenton, New Jersey, sea-level test cells with ram-air capability were also added to the complex at AEDC.

Until recently, some of the older AEDC turbine engine test facilities still used compressors transferred from Germany after World War II. Over the past few years, AEDC has made a very large investment in modernizing the plant infrastructure for the turbine engine test cells to improve the efficiency and reliability of the facilities. Similar to the wind tunnels, service life extension program initiatives will keep these facilities viable for some time to come, but in 25 years the primary infrastructure for turbine engine testing at AEDC, as well as the nation, will be at least 50 years old.

State of the technical workforce

The skills, expertise, and experience of the T&E workforce are as critical as the test facilities. Over a period of years, reductions in budget, changes in funding policies, and acquisition reforms have had an unintended consequence of restricting the engineers and scientists at ground-test facilities from developing and applying their analytical skills. In addition, the accumulation of well-meaning policy dictates and process controls has further stifled development of ground-testing technical expertise. More emphasis has been placed on having test engineers manage cost and schedule of test projects, eroding the time available to evaluate the test environments and systems under test. In assessing these trends, we argue that the DoD has put too much emphasis on improving the efficiency of testing (reduced test scope, fewer facilities, fewer personnel) and not enough emphasis on good systems engineering and enhancing the effectiveness of testing (catching system defects early and supporting remedial actions). This misplaced emphasis fails to address the root causes for excessive cost and schedule delays in major acquisition programs. AEDC believes having experienced scientists and engineers with appropriate testing domain knowledge is critical to increasing the effectiveness of T&E in acquisition programs. AEDC has consequently made rebuilding the technical excellence of its workforce one of the highest priority strategies for the future of the Center (Best, Kraft, and Huber 2008; Huber et al. 2009).

Requirements for future aeronautical development capabilities

With an aging infrastructure, and a work force that needs to be technically rebuilt, what will be the future for aeronautical ground testing? In the immortal words of Yogi Berra, "the future ain't what it used to be." Beyond trying to forecast the need for aeronautical ground testing, we prefer to generate a future vision for aeronautical ground testing that anticipates and enables future advances much as Arnold and von Kármán did in their time.

Will we keep using ground-test facilities?

With fewer aeronautical systems under development and advances in M&S, it is a legitimate question to ask whether we will require wind tunnels and propulsion test facilities in, say, 25 years. The short answer is "absolutely!"

Although there are fewer flight systems projected to be developed in the future as compared with the heyday of the 1950s and 1960s and even during the "Reagan buildup," there are clearly persistent requirements for new vehicles, including sixth-generation fighters, advanced unmanned air vehicles (UAV), next-generation bombers, advanced air armament, high-speed–hypersonic weapons, and launch systems. Anything launched into space also has to fly through the atmosphere—twice if there is a return leg.

In the next 25 to 50 years, there will be little change in the nature of aeronautical systems. Aircraft will still be the major form for domestic and global transportation. Even with the changing nature of warfare, the military will still rely on aeronautical systems (manned or unmanned) for the transport of troops and materiel, and for the delivery of both kinetic and nonkinetic effects. Kinetic weapons will be very similar aerodynamically to those in use today. Although new materials, morphing structures, and nanotechnology may improve the performance of flight systems, the basic function of generating the forces and moments for flight will result from the shape and deflection of aerodynamic surfaces. Propulsion systems will evolve further, but will still rely on the conversion of hydrocarbon fuels into thrust. There is a potential for hydrogen-based propulsion systems to emerge as an alternative, but the time frame required to advance the technologies to make them practical as well as the enormous cost of converting the worldwide fleet of aircraft and the supporting infrastructure to hydrogen will occur later rather than sooner. There will be significant advances in efficiency, but not a radical shift to new modes of long-range transportation. The major changes to aeronautical systems will be in sensors, avionics, and networking. Wind tunnels and engine test cells will still be the primary sources of information on performance, operability, and durability for the development and sustainment of aeronautical systems.

Frequently, when questions are asked about the future need for wind tunnels or engine test facilities, a myopic viewpoint is taken that the long-range requirements for test capabilities are primarily driven by future systems. In reality, the primary workload in the major ground-test facilities will be in support of existing systems. New programs require a surge in capacity, but they are not the major driver for availability. A large majority of test time in today's ground-test facilities is used for weapon certifications, block upgrades, support to foreign military sales, component improvement programs (CIP), etc. Typical examples include certifying the Small Diameter Bomb on fielded aircraft, which requires wind tunnel store separation testing on the F-15E, F-16, F-18, and the F-22. When the F-35 reaches operational status, it too will go through a comprehensive safe separation certification process to clear inventory weapons. Similarly, the F-100 and F-110 turbine engines introduced in the 1970s are still undergoing CIP testing in turbine engine cells. The F-119 engine for the F-22 is already in a CIP program although the aircraft has only recently entered the fleet. Because weapon systems being introduced today will be expected to stay in the inventory for at least 40 to 50 years, it is clear that there will be a continual need to provide ground-based flight simulation tools to support upgrades and sustainment over their life cycles.

Although some view the aeronautical field as a mature one, the era of "higher, faster, further" is not over yet. Even though man has flown on the Space Shuttle to space and returned at tremendous speeds (Mach 25), high-speed hypersonic flight systems still remain a major challenge. The challenge is to make hypersonic flight practical and affordable through the use of air-breathing propulsion systems instead of rockets. The ground-test facilities to adequately and accurately simulate hypersonic flight conditions are still in development. Hypersonic test facilities will be more crucial to the development of flight systems than traditional lower speed tunnels. That said, a discussion of the facilities necessary to support development of hypersonic weapon systems is beyond the scope of this paper. Hence, we will focus primarily on subsonic through low-supersonic flight systems. A roadmap for future hypersonic facility needs is presented in Fetterhoff et al. (2006).

And, what of the "holy grail" of replacing "expensive" test facilities with M&S? This persistent myth will not be realized in the next 25 years for a number of reasons:

- M&S in the broader defense community usually refers to combat engagement and higher-level campaign modeling. Although these tools are exceptionally important for training, war-gaming, and requirements definition, they have limited application to physics-based design, prototyping, testing, analyzing, fixing, fielding, and sustainment of warfighting systems.
- High-fidelity, physics-based, constructive modeling, such as computational fluid dynamics (CFD) and computational structural dynamics (CSD) have made tremendous strides in the last several years (Kraft and Matty 2005) and will advance even further as modern computer systems provide peta-flop scale (10^{15} floating point operations) computing throughput. At a minimum, however, test facilities will be required to validate these models. Furthermore, the state of the art in modeling certain physical phenomena such as turbulence and separation is still not sufficient to use CFD as a replacement for testing over the entire envelope of a flight vehicle.
- CFD and CSD will be useful tools for evaluating design and performance of flight vehicles, but they will not be able to supplant the need for ground-test facilities to determine the operability and durability of flight and propulsion systems.

The previous assessment notwithstanding, M&S integrated with T&E methodologies will be a major enabler for changing the effectiveness of the acquisition process. We will explore this assertion in subsequent sections of this article.

Efficiency versus effectiveness

There is an interesting dichotomy in the use of ground-test facilities for aeronautical development. Even though significant investments have been made to increase the efficiency of producing data in wind tunnels (Kegelman 1998; Melanson 2008; Peters et al. 1999), and more and more M&S has been applied to the design and development process, the total wind tunnel hours used for a typical development program has tended to remain constant at about 22,000 hours per vehicle. Similarly, ground testing of turbine engines averages about 13,000 hours in turbine engine cells. In part, the constancy of test hours can be attributed to the increasing complexity of the vehicles. However, the major reason the test hours remain relatively constant is that the aeronautical community has not really worked to refine and optimize testing. The test plans from program to program tend to stay relatively the same. For example, the baseline wind tunnel campaign for the F-22 in AEDC's transonic Tunnel 16T, which was performed from 1991 through 1994, has almost identical content and cycle time to

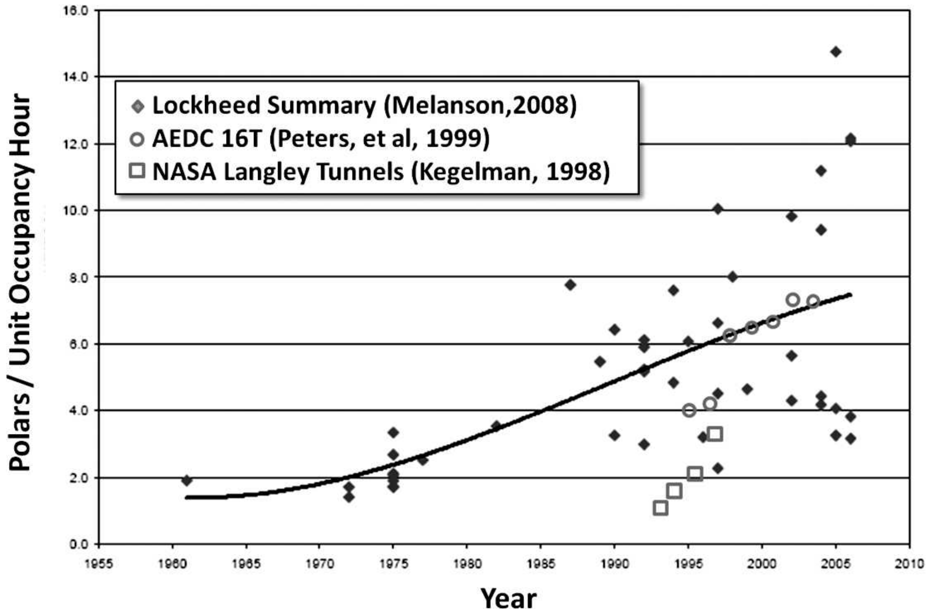

Figure 3. Facility productivity for ground test facilities. Improvements came about after very considerable investments in faster data systems, major modifications to minimize nontest time, and advanced test techniques such as continuous pitch testing.

the baseline campaign for the F-35 conducted over a decade later. During the intervening period, significant emphasis was placed on increasing data productivity in wind tunnels. As shown in *Figure 3*, data productivity essentially increased by half from the early 1990s to the mid-2000s.

Continued emphasis on the *efficiency* of producing data has marginal return on investment. The cost of a wind tunnel campaign for development of a twin engine fighter is about 5 percent of the overall cost of T&E. In turn, the total cost of T&E for a development program is generally just a few percent of the total development cost. Hence, a 50 percent reduction in the unit cost of a wind tunnel campaign equates to just a few tenths of a percent reduction in program costs. The efficiency gains in wind tunnel testing are easily lost through increases in energy costs, which are typically 50 percent of the cost of testing in a ground facility.

On the other hand, increasing the *effectiveness* of ground testing can have a relatively profound impact on program costs. Effectiveness in the context of this article means the ability to reduce the overall cycle time for development while minimizing the need for rework of late defect discoveries. To compare the difference between efficiency and effectiveness, we can use a simple example. If we could magically eliminate the cost of a wind tunnel campaign during the development cycle of a major fixed-wing aircraft, we could save at best about one half the cost of one avionics package for an aircraft such as the F-22. On the other hand, if we could optimize the use of the wind tunnel to reduce overall cycle time by 1 month for a program like the F-35 (which has a resource burn rate on the order of $1 billion/month), we could save the equivalent of five to seven aircraft.

With the current national capacity for ground testing, a typical wind tunnel campaign for a modern military fixed-wing aircraft requires 3 to 4 years. Although wind tunnels will remain the primary design verification and development tool for flight systems for the foreseeable future, there is a driving demand to reduce the RDT&E cycle to just a few years. This demand will require an aggressive change in how wind tunnels are used in the future for them to remain a viable part of the aeronautical RDT&E process.

The primary objective measure for determining the effectiveness of aeronautical testing is the cycle time for the acquisition program in development. We submit that T&E cycle time reduction will have a greater overall influence on decreasing program costs than any other cost-cutting strategy. Reducing development costs leaves more funds available for procurement, which has the compound effect of permitting larger quantity buys, which in turn cuts unit costs. Cycle time can be estimated by the following relationship:

$$\mathit{Cycle\ Time} \sim \frac{\mathit{Workload}}{q \cdot \mathit{Capacity}}.$$

In this expression, *Cycle Time* is the total time required to perform the ground test campaign; *Workload* is the total amount of testing operands to be accomplished (e.g., unit occupancy hours, data points, etc.); q is a quality measure that indicates the fraction of the total

work that is done right the first time (i.e., the inverse of late defects and rework); and *Capacity* (measured in testing operands per unit of time), which depends on the availability of the test infrastructure, the staffing to use the facilities, and the throughput. The three primary levers to decrease cycle time are reducing the workload required, minimizing rework, and increasing capacity.

The total workload involved is primarily process driven. If a wind tunnel campaign for a major fixed-wing aircraft requires about 22,000 hours of wind tunnel testing, then given today's national capacity of about 6,000 h/y, such a campaign requires 3 to 4 years to conduct. As discussed earlier, wind tunnel campaigns are traditionally designed around test hours, not test points. That is why the fourfold increase in productivity illustrated in *Figure 3* had essentially no impact on reducing the number of wind tunnel hours for the F-35. Given more efficient throughput, the users of wind tunnels take more data, rather than reducing test hours. Anecdotal discussions with several aircraft companies over the years strongly suggest that a large fraction of the data acquired in the wind tunnel is not used but is retained as a "security blanket" in case an anomaly arises. Reengineering the way wind tunnel data are obtained and used has the potential to be a major driver for increasing the effectiveness of ground testing.

Similarly, the inverse of q, the amount of rework normally performed, is also process driven. For most aerospace systems in development, q is approximately 0.25, resulting in 4 to 10 rework cycles. The incremental increase in program costs is proportional to $(1/q) - 1$, indicating the potential to easily double development costs through late defects and rework. The best way to minimize the impact of rework on cycle time is early discovery of defects. This will entail improvements in design methodologies employed by aircraft companies coupled with improvements in wind tunnel testing and modeling techniques. These latter improvements minimize any defects in design being passed downstream to flight testing, where the cost of fixing the defect increases an order of magnitude. Also, feedback loops from discrepancies found in flight testing back to ground testing and back to design methodology need to be institutionalized to make further improvements.

A primary target for decreasing rework is improving the early determination of the impact of steady and unsteady flow effects on the vehicle structure. Historically, most aircraft development programs have discovered 10 structural flaws in flight with varying degrees of cost and schedule impacts that can reach a billion dollars and a year to overcome. As can be seen from this example, increasing q (decreasing late discoveries) will have a profound impact on development cycle time and cost.

In contrast to process-driven parameters, the capacity of a ground-test facility is primarily budget driven. Capacity equals the availability of the capability times the shift staffing available to provide the capability times the throughput. The availability of the equipment depends on investments in maintenance and reliability. Also, the budget determines whether a facility is staffed for one, two, or three shifts. Staffing is the most dynamic variable for increasing or decreasing capacity. Throughput (e.g., test points per hour) is also budget driven. The facility productivity improvements shown in *Figure 3* came about after very considerable investments in faster data systems, major modifications to minimize nontest time, and advanced test techniques such as continuous pitch testing. Increasing capacity of existing facilities is the least effective of the three parameters for significantly decreasing acquisition cycle time. However, developing and funding new facilities with capability and capacity optimized to maximize throughput using the reduced workload and defect avoidance and discovery approaches suggested in the previous discussion would be a powerful adjunct to process reengineering.

The discussion on cycle time focuses on the cycle time for testing. To aggressively attack the cycle time for development of a new flight system, one also needs to address the contributions to cycle time from design, prototyping, analysis of results, and other development and manufacturing maturation activities. There is potential interplay between these processes and those from test that can further help reduce overall cycle time. In this article we are focused on reducing the cycle time for testing.

Reengineering the aeronautical system development process to increase effectiveness

The nation finds itself at a strategic crossroads relative to the future use of aeronautical ground-test facilities. The major infrastructure for aeronautical ground testing is now approaching 50 years of age and is considered a mature industry. All organizations or industries that have evolved through a pioneering and transitional phases to a mature phase come face-to-face with a critical strategic decision. On the one hand, they can accept decline and continue current practices. This prescription for decline is a "harvest" strategy; that is, eliminate investing, maximize cash flow from the business, and eventually accept divestment (Porter 1980). This translates, in the case of ground-test facilities, to continued erosion of technical expertise,

providing testing services as a pure commodity with no knowledge-based value addition, maintaining the infrastructure as long as reduced budgets permit, and then abandoning or razing the facilities.

An alternate strategy for a declining organization is to reinvent its business. AEDC has chosen a multifaceted approach incorporating people, processes, and facilities to reinvigorate T&E by focusing on the effectiveness, not just the efficiency, of the test processes.

Typically when one discusses the attributes of future facility needs, the conversation tends toward future program requirements and decisions on the optimum size for the facility and its operating range (e.g., pressures, temperatures, velocities, Reynolds numbers, etc.). Instead we will focus on desired attributes that will increase the effectiveness of future facilities guided by our thoughts presented in the previous section. We will focus most of our attention on changes to how we conduct testing rather than on descriptions of future test facilities. These changes to how we will do testing in the future will involve aggressive use of M&S as well as improved test methodologies.

The primary target for reengineering aeronautical ground testing to increase effectiveness is to reduce the overall workload without increasing risk. A major contributor to the number of wind tunnel test hours is the need to generate about 2.5 million data points to determine the stability and control (S&C) of the vehicle. This is traditionally done in the one-factor–at-a-time (OFAT) mode where data are obtained for each model configuration, orientation, speed, and simulated altitude over the entire operating envelope. This ponderous number of data points also has been the primary reason that CFD has not made greater inroads into developmental wind tunnel testing. Estimates to compute the equivalent 2.5 million OFAT points range from approximately 100 to 1,200 years using existing computer tools.

Recently, the CFD community (Dean et al. 2008) introduced an innovative and efficient computational method for accurately determining the static and dynamic S&C characteristics of high-performance aircraft. In contrast to the "brute force" approach to filling an entire S&C database for an aircraft, an alternate approach is to reduce the number of simulations required to generate a complete aerodynamic model of a particular vehicle configuration at selected flight conditions by using one or a few complex dynamic motions (e.g., varying frequency and amplitude over a dynamic trajectory) and nonlinear system identification techniques. This approach now makes CFD a reasonable source of S&C data for an aircraft. Interestingly, there is a comparable experimental technique using the prefiltered dynamic output from the force–moment balance used in the wind tunnel, system identification techniques, and a "fly the mission" profile in the wind tunnel.

As indicated in *Figure 4*, using these advanced "fly the mission" modeling and testing methodologies combined with DOE offers an innovative, aggressive approach to reducing the overall test workload. Attempts to apply DOE to streamline a traditional individual wind tunnel test have been only marginally successful because current wind tunnels are not conducive to rapidly changing parameters to optimize randomness of the data set. However, if one shifts to thinking about DOE at the "campaign" level, there may be a more productive approach to using DOE.

Instead of the OFAT approach to building the colossal database characteristic of today's aeronautical development processes, an approach using DOE response surface techniques could be more effective. A response surface is a mathematical construct that represents the parameter space along which the characteristics of the vehicle are captured. An example of the use of response surface modeling for aerodynamic configurations is given in Landman et al. (2007).

In contrast to traditional OFAT approaches that basically fill up the entire parameter space and try to interpolate to determine the characteristics of the vehicle, an initial response surface could be built using simple engineering models. Of course, the uncertainty over the response surface would be high, but more refined high-fidelity physics modeling could then be efficiently applied to reduce the uncertainties over the response surface using the fly-the-mission approach mentioned previously. Those areas on the response surface that still exhibit a high degree of uncertainty then become the primary focus for the wind tunnel test campaign, i.e., the focus is put on key areas for risk reduction versus defining the entire parameter space. DOE helps determine the minimum number of computations or test points to reduce uncertainties in areas of interest on the response surface. Finally, the areas of residual uncertainty become the primary interest for focused flight testing, which serves to reduce the overall workload for that phase of testing. In this manner, the overall amount of testing could be dramatically reduced with a commensurate impact on total cycle time.

The mathematics of the DOE methodology helps ensure that the optimum data set are taken. The alpha and beta (or power coefficients) of the DOE process can be used to address how much further variance can be reduced on the response surface by an additional calculation, wind tunnel test, or flight test. There is a point at which doing another CFD solution will not

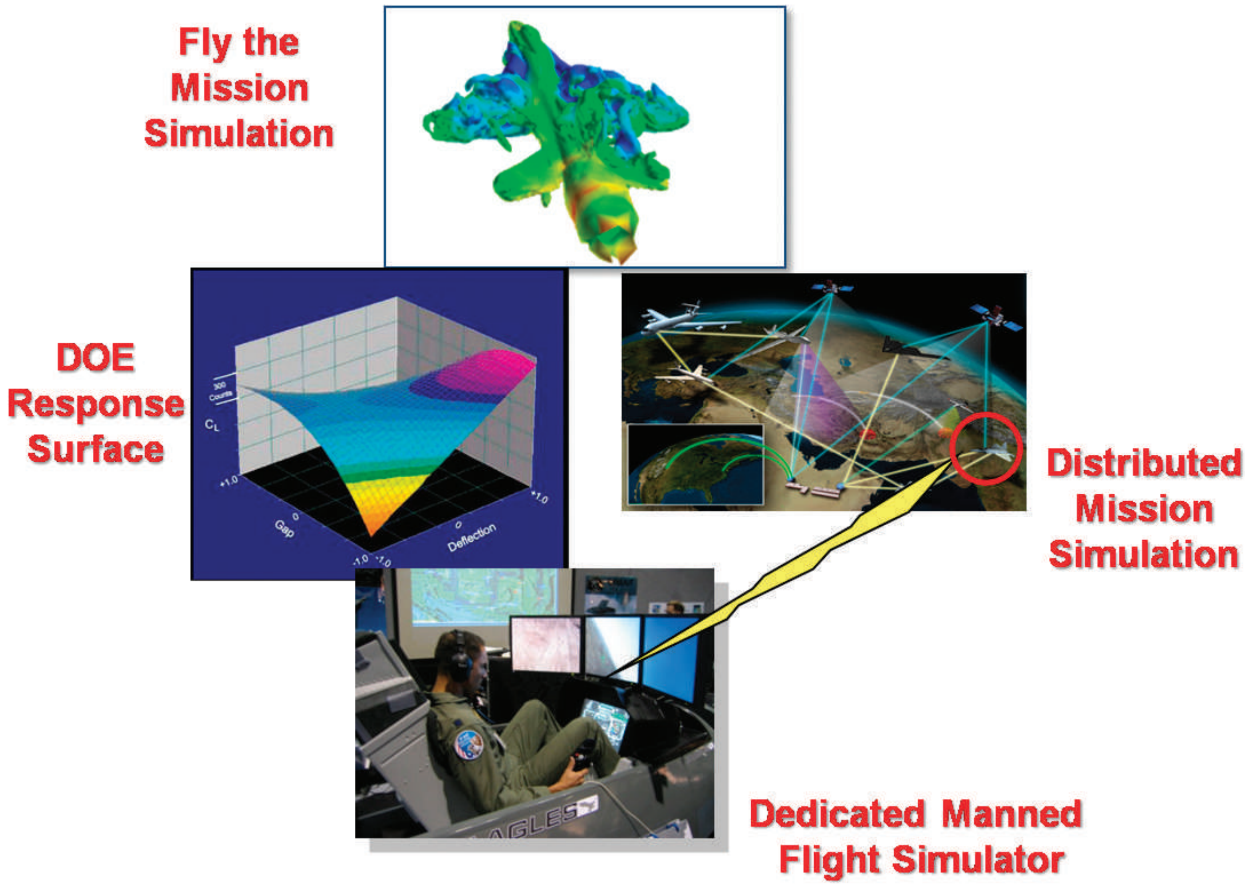

Figure 4. Fly the Mission Model with Design of Experiment (DOE) applied. This manned flight simulator can begin to address some of the operational integration issues early in the program, thereby allowing integrated DT/OT earlier.

reduce uncertainty further; hence, one needs to move on to wind tunnel testing. Likewise, there is a point of diminishing returns for doing another wind tunnel test, and the program needs to move on to flight testing. Thus, unnecessary modeling and/or testing can be minimized. The beta coefficient also provides some insight into the probability that a defect is being passed downstream to the next development step.

The response surface method also provides an invaluable approach to supporting integrated developmental testing (DT) and operational testing (OT) as well as addressing networking and interoperability issues. The characteristics of the vehicle captured in the response surface can be translated directly into the performance math engine for a manned flight simulator as suggested in *Figure 4*. Even at the earliest phases of development, this manned flight simulator can start to address some of the operational integration issues, thereby allowing integrated DT/OT earlier in the program. If early brass-board or digital models of the avionics and communications packages are brought into the manned flight simulator, the evolving performance of the system can be evaluated as a node in a distributed mission simulation. Feedback from this integrated approach can be used in the very early stages to improve the design for maximum performance as an interoperable system. Today, most of the OT interface issues, as well as interoperability, are not addressed until very late in the development process. The overall impact on reducing development cycle time using such an innovative approach could be immense.

A key to increasing the quality, q, or decreasing the amount of rework, is earlier and better integration of major subsystems such as the airframe and structure, the airframe–propulsion systems, or the airframe–weapon systems. Most defects occur at the interface of major subsystems. Current practices generally address system integration issues later in the development process, which maximizes the amount of rework required (and increases associated costs) if a defect is discovered. Key enablers required to get earlier insights into integration issues include high-fidelity multi-disciplined modeling capabilities and advanced on-body and off-body flow diagnostic techniques such as pressure-sensitive paint (PSP) and planar Doppler velocimetry (PDV).

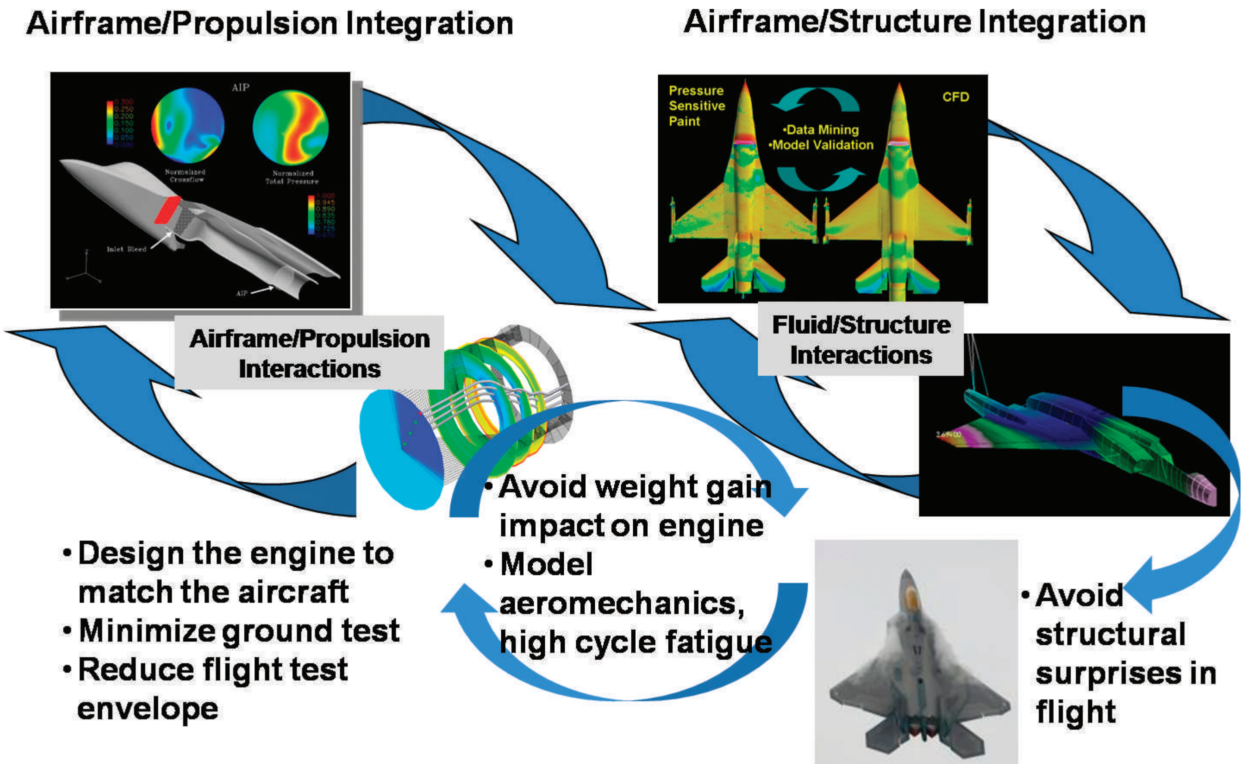

Figure 5. The interplay of high-fidelity multidisciplined modeling capabilities and advanced on-body and off-body flow diagnostic techniques reduce the number and impact of late defect discoveries.

An example of the interplay of these enablers to reduce late defect discoveries is suggested in *Figure 5*. Multidiscipline, high-fidelity CFD/CSD can be used earlier in the design cycle to examine interactions between major subsystems such as the airframe and structure or airframe and propulsion system. Traditionally, pressure loads data are obtained on a very early (and expensive) wind tunnel model specifically designed with hundreds to a few thousand pressure taps on the surface of the model. These pressure loads are provided to the structural engineers to perform a structural analysis and design of the vehicle. While the structural engineers are doing their analyses, the aerodynamicists are usually continuing to refine the outer mold lines of the vehicle to improve performance. Because of the cost and complexity of wind tunnel pressure models, effects on pressure loads due to changes in outer mold lines are usually not updated. When the airframe and underlying structure are integrated into the first set of flight vehicles, it is not uncommon to find structural flaws. (Remember that on average 10 structural flaws are found on each major aircraft development during flight testing.) Contributing to these late discoveries are inadequate characterization of the dynamic interactions between fluids and structures as well as a lack of integration of aerodynamic and structural analysis tools.

The application of peta-scale computing in the near future will enable integrated modeling of aerodynamics, structures, and propulsion systems during the design process. The ability to integrate these multiple disciplines will address many of the subsystem issues early on. Advanced diagnostic tools such as PSP in ground-test facilities will not only enable model validation, but will better help characterize the dynamic flow-field effects on flight vehicle structures. PSP will also permit rapid updating of flow-field loads as part of structural analyses without having to build or update pressure models.

Minimizing potential weight growth of the airframe structure to account for defects discovered in flight can also have an important effect on the development of the propulsion system. Frequently, when weight growth occurs late in the development cycle because of structural changes, the propulsion system developers are tasked to produce more thrust to ensure meeting vehicle performance parameters. It is not uncommon for the engine developer to have to significantly improve the performance of the engine fairly late in the development cycle. All of these interactive weight issues also affect control surface effectiveness and control system gains. This conflicting interplay between the various subsystems is a contributor to late cycle churn and program delays.

Also suggested in *Figure 5* is the potential for sharing some of the same modeling methodologies between the structural analysts and the propulsion system designers. The fluid–structure interactions that drive structural design exhibit the same fundamental physics as the fluid–structure interactions on the aeromechanics of fan and compressor blades. Advances in integrated CFD/CSD tools will help in better understanding and avoiding potential high-cycle fatigue issues earlier in the design cycle.

Figures 4 and 5 present an aggressive use and integration of modeling and ground testing simulation methodologies to change the future effectiveness of aeronautical development. It is clear that various test capabilities cannot be addressed and judged in isolation but must be treated as an integral combination with technical expertise, improved processes, and better test methods to achieve the desired state of effectiveness.

Enabling capabilities for increasing aeronautical development effectiveness

Through a confluence of DOE application and emerging advances in M&S, data systems, test techniques, flow diagnostics, and networking, the concepts for dramatically reducing the overall cycle time for development of aeronautical systems presented in this article are achievable in the near future. Advancing capabilities needed to support the future effective approach are summarized in the next section.

Advanced integrated high-fidelity physics-based constructive modeling

Advanced computational fluid dynamics and structural dynamics are key enablers for achieving much of the vision for more effective aeronautical development. Rapid advances in networks and clustering will make peta-flop computing available in the next few years. Computing power of this magnitude will allow complex multidiscipline problems to be attacked in hours versus weeks. The Office of the Secretary of Defense (OSD) High Performance Computing Modernization Office is investing in advanced constructive modeling techniques to maximize the use of this computing power to affect DoD acquisition programs. The OSD's vehicle to execute these investments is the Computational Research Engineering and Acquisition Tools Environment (CREATE) program initiated in fiscal year 2008 (FY08). CREATE is building software capability to improve naval ship, radio frequency antennae, and air vehicle design tools. The air vehicle component (CREATE-AV) is developing tools for simulating a full up-and-away maneuvering aircraft, fluid–structure interactions, and airframe propulsion integration for fixed and rotary-wing aircraft. Applications of the CREATE-AV tools to the ideas presented in this paper are highlighted in Kraft (2007).

Design of experiments

Design of experiments is not a new capability, but recently more emphasis has been placed on incorporating DOE into RDT&E processes (Hutto and Higdon 2009). The benefits of using DOE include: scientifically and objectively constructed tests; pretest evaluation of the ability to pass good systems and detect poor systems; resource alignment to "right size" tests; execution guards against day-to-day variations; and analysis by system experts in a rapid, objective, and accurate fashion. The DOE methodology must be fully extended to the ground-test and flight-test campaigns to increase their effectiveness.

Data merging and data mining

A data mining software package (DATAMINE) has been developed and applied at AEDC to minimize errors introduced in the wind tunnel data acquisition process and provide mining tools to search and access historical test data in common data files (Skelley, Langham, and Peters 2004). Concurrent with the enhancements for mining and display applications, a data validation manager has been put into place to ensure that accurate data were being acquired. This was accomplished with the incorporation of data mining interface and protocols to common and relevant models and previously obtained data for dynamic online comparison with wind tunnel data. Examples of expectation models and data include engineering methods aerodynamic prediction codes, high-fidelity constructive models, and aerodynamic models based on historical or predicted data. To support future needs, we must extend such data mining tools to interface with the DOE response surface methodologies, i.e., previous models and data sources need to be adapted to the response surfaces describing the system performance including a description of the residual variance in the quality of the information.

Advanced on-board/off-board diagnostics

Flow diagnostics to measure pressures, temperatures, velocities, flow directions, and shear stresses have been under development for several decades. PSP has matured to become a practical and accurate technique for determining the pressure loads over a complete three-dimensional body (Sellers 2005). PSP eliminates the need for a very expensive instrumented loads model, and PSP pressure maps can be used to update structural loads "on the fly" as geometry is changed to improve performance. Off-body measurement techniques such as laser PDV, stereoscopic particle image

velocimetry (PIV) (Ruyten, Williams, and Heltsley 1994), and planar laser-induced fluorescence (PLIF) (Reinholz et al. 2008) have advanced to being practical measurement tools in production test facilities. These off-body diagnostic tools serve a threefold purpose: better validation of CFD models, particularly at high angles of attack; understanding scale effects in ground-test facilities; and additional insight into flow features that affect aerodynamic performance.

Networking

In the next generation, the physical location of ground-test facilities will be a secondary consideration. Virtual control rooms are already in existence that let Eglin Air Force Base customers for AEDC wind tunnels participate from Eglin essentially in the same manner as they would if they were present in the control room at Arnold Air Force Base (Muerle 2007). However, in the future, virtual connections need to expand significantly beyond just moving data around the country. Connecting ground-test facilities to manned flight simulators to address DT/OT integration issues as well as networking and interoperability issues will require innovative changes to modeling and data management processes using standards such as those defined by the Joint Mission Environment Test Capability program through its Test and Training Enabling Architecture.

Implementing new technologies to maximize effectiveness will require changes to test facilities. Furthermore, older facilities will eventually reach a point where they become too costly to sustain and upgrade, and building new is more cost effective. However, when such thresholds are reached, these moments become opportunities to design from the outset facilities whose functionality reflects comprehensively our vision for how to conduct aeronautical ground testing. Some of the attributes required for upgrades to current facilities or for future test facilities include:

- Ability to install and deinstall test articles in minutes to support focused tests in areas where primary uncertainties exist and to optimize use of DOE.
- Ability to rapidly prototype and manufacture models reflecting design changes that are instantly transmitted by customers of ground test facilities to their test partners using the latest in compatible CAD/CAM and model shop tools and materials.
- Ability to efficiently modify test conditions or proceed through a test point matrix to minimize energy usage while reflecting to the maximum extent DOE considerations.
- Convenient and thorough optical accessibility for flow diagnostics tools such as PSP, PDV, PIV, PLIF, etc.
- Connectivity to high-performance computing capabilities to integrate and merge computer simulations and test data.
- Advances in data mining and data merging software as an integral part of the facility data systems to enable rapid analyses of the variances along response surfaces.
- Virtual presence, networking, and connectivity to achieve a fully integrated DT/OT approach in an interoperable environment.

Certainly, another key consideration in the next generation of test facilities is that they be energy efficient. For current major test facilities, the cost of energy is approaching 50 percent of the total cost of testing. It is expected that in the future energy costs will become an even larger fraction of the operating costs of current facilities. The large facilities in use today were designed for technical performance, not energy efficiency. Although many upgrades have been made to these facilities to increase energy efficiency, there is limited return on continuing to try to reduce energy costs in legacy facilities.

Because energy usage is proportional to the cross-sectional area of a wind tunnel, the size of future facilities needs to be balanced between energy use and data quality. Optimizing future facilities for rapid installation and deinstallation of test articles and rapid changes in test conditions not only supports better use of DOE but also minimizes energy usage. Future wind tunnels may also need to be sited to make maximum use of renewable energy sources such as hydro, hydroelectric, geothermal, wind, or solar energy.

In addition, future facilities need to be "green." The operations of advanced facilities of the future need to be evaluated from a total systems approach. Considerations such as closed recovery systems for cooling water, hydraulic fluids, etc., not only can reduce the overall use of energy for the facility, but also better protect the environment. Waste heat from closed cooling systems can be used to heat buildings or generate electricity for lighting buildings, etc. Use of hazardous materials must be minimized and when released, immediately and easily remediated. Industries that have taken a total systems approach have found significant cost savings in addition to minimizing environmental impact (Senge et al. 2008).

To achieve these attributes—from DOE optimization to energy efficiency—a new, more sophisticated approach to facility design is required. To this end AEDC has formed a small group of experts experi-

enced in wind tunnel development and operation to begin conceptualizing what a next generation wind tunnel might look like. They have been charged to put particular emphasis on introducing the requirements discussed in this article and on developing analysis tools that enable insightful negotiation of the design trade space. That this group is approaching the task with an open mind and without preconceived notions is evident in their recognition that the result may not look anything like today's facilities and may indeed turn out to be a radical departure from traditional designs. Initial entreaties to NASA to collaborate on this endeavor have been met with a positive response.

More important than these technical advances, the agility and skills of the workforce are paramount. Our experiences to date (Best, Kraft, and Huber 2008; Huber et al. 2009) have convinced us that the best hope for the future of the RDT&E community is to *make investment in the technical competence of the workforce a top priority*—on par with, if not exceeding, any test infrastructure improvements or sustainment. This investment must be holistic in the sense that it addresses the full spectrum of features that go into developing and sustaining a competent workforce: advanced education, continuous learning, hands-on experience, reduced administrative burden, collaboration opportunities, as well as a cultural environment that is conducive to innovation and that demands technical excellence. As we have faced the never-ending challenge of balancing resources to provide test capabilities to our customers, we have been repeatedly reminded that having test cells or test ranges without accompanying expertise to operate them and to understand their interactions with systems under test is a hollow capability indeed.

Summary/conclusions

Forgive us if we (mis)appropriate the famous Mark Twain quote, "the report of the death of aeronautical ground-test facilities is an exaggeration." That said, we recognize that to question the future relevance of ground-test facilities if they do not evolve to meet the demands of the future is both healthy and warranted. We acknowledge that to be a viable component in the development process of future systems, aeronautical ground test capabilities need to be dramatically changed to be more effective.

Numerous national panels have authored studies on aeronautical ground-test facilities, each study trying to decide which ones are critical to DoD and NASA needs. The emphasis in these studies tends toward trying to determine which facilities can be divested. In their current configuration and using current test methodologies, the nation probably already has the minimum set of wind tunnels and turbine engine test cells to support development programs. Further reductions in facilities and capabilities will negatively impact development cycle time for acquisition programs if only traditional approaches continue to be employed.

We need to modify our business models for the sustainment and use of ground-test facilities (and other facilities as well). Instead of focusing on trying to maximize usage of any given facility to provide the best return on investment (ROI) for that facility, we need to optimize the effectiveness of the use of all of our facilities to minimize cycle time. Analogous to the theory of constraints model, keeping all machines on a shop floor fully utilized is not the best way to increase throughput and reduce costs. The ROI for our test facilities needs to be based on the impact to the overall cycle time and costs of the program under development.

Now is the time as a nation to build and pursue a bold vision for the capabilities (people, processes, and facilities) required for the next 50 years of aeronautical system development. We, as a community, need to generate a modern version of the leadership demonstrated by General Hap Arnold and Dr. Theodore von Kármán, and create the vision that will sustain us for the next half century of aeronautical systems development. Instead of continuing to conduct studies to determine which facilities we can divest, it would be much more productive to pursue advanced capabilities to maximize the effectiveness of testing within the development process. Our nation's economic viability and security foundation as an aerospace power depend on it. ❑

DR. EDWARD M. KRAFT is the chief technologist at AEDC. He is a member of the Senior Leadership service. He has over 40 years experience in T&E. He has been a leader in the innovative integration of M&S with ground and flight test. He has also been instrumental in developing metrics to better assess the value of T&E to the acquisition process. He holds a bachelor's degree in aerospace engineering from the University of Cincinnati and master's and doctoral degrees in aerospace engineering from the University of Tennessee Space Institute.

COL ARTHUR F. HUBER II is the commander of AEDC. He has held a variety of assignments in the Air Force specializing in air and space testing, tactics development, and various areas of systems acquisition and sustainment. He has been assigned as officer aircrew in multiple aircraft systems accruing over 500 flying hours. He was commissioned in 1983 as a distinguished graduate of the Air Force Reserve Officer Training Corps program. He holds bachelor's and master's degrees in aerospace engineering from the University of Notre Dame, a bachelor's degree in

government and international relations also from Notre Dame, and a master's degree in strategic studies from the Air War College. Additionally, he is a flight test engineer graduate of the USAF Test Pilot School.

References

Best, J. T., Edward M. Kraft, and Arthur F. Huber. February 2008. "Revitalizing the Technical Excellence of the Workforce at the Arnold Engineering Development Center (AEDC) and Beyond," AIAA Paper 2008-1611.

Davis, John W., Bill Stamper, and Paul Wiggum. January 1996. "The National Wind Tunnel—Current Status," AIAA Paper 1996-226-451.

Dean, John P., Scott A. Morton, David R. McDaniel, James D. Clifton, and David J. Bodkin. August 2008. "Aircraft Stability and Control Characteristics Determined by System Identification of CFD Simulations," AIAA Paper 2008-6378.

Fetterhoff, Thomas, Edward Kraft, Marion L. Laster, and William Cookson. July 2006. "High-Speed/Hypersonic Test and Evaluation Infrastructure Capabilities Study," AIAA Paper 2006-8043.

Hansen, James H. 1992. "Engineer in Charge—A History of the Langley Aeronautical Laboratory, 1917–1958," NASA SP-4305.

Huber, Arthur F. II, Edward M. Kraft, John T. Best, Phillip B. Stich, David A. Eldridge, William B. Baker, and Peter A. Montgomery. February 2009. "Growing Technical Excellence in the AEDC Workforce." AIAA Paper 2009-1762.

Hutto, Gregory T., and James M. Higdon. February 2009. "Survey of Design of Experiments (DOE) Projects in Development Test CY07-08," AIAA Paper 2009-1706.

Kegelman, Jerome T. January 1998. "Accelerating Ground Test Cycle Time: The Six-Minute Model Change and Other Visions for the 21st Century," AIAA Paper 98-0142.

Kraft, E. M. May 2007. "A CREATE-AV Approach to Streamlining Aeronautical Vehicle Acquisition through M&S," presented at the Air Force Modeling and Simulation Conference. May 7–11, 2007. Williamsburg, VA.

Kraft, E. M., and Jere J. Matty. 2005. Application of high performance computing at the Arnold Engineering Development Center (AEDC). *ITEA Journal* 26 (2): 55–60.

Landman, Drew, Jim Simpson, Dan Vicroy, and Peter Parker. 2007. Response surface methods for efficient aircraft configuration aerodynamic characterization. *Journal of Aircraft* 44 (4): 1189–1195.

Launias, R. D., T. B. Irvine, and E. A. Arrington. January 2002. "NACA/NASA and the National Unitary Wind Tunnel Plan, 1945-1947," AIAA Paper 2002-1142.

Melanson, Mark R. January 2008. "An Assessment of the Increase in Wind Tunnel Testing Requirements for Air Vehicles Over the Last Fifty Years," AIAA Paper 2008-830.

Muerle, Douglas C. February 2007. "The Development and Evolution of a Remote Wind Tunnel Control Room at Eglin AFB," AIAA Paper 2007-1634.

Peters, William L., W. R. Lawrence, L. Michael Mills, and William E. Milam. January 1999. "Cycle Time Reduction Strategies and Improvements in Transonic Testing in the AEDC Wind Tunnel 16T," AIAA Paper 99-0179.

Porter, Michael E. 1980. *Competitive strategies—Techniques for analyzing industries and competitors*. New York: The Free Press.

Reinholz, Carrie K., Fred L. Heltsley, James R. Sirbaugh, Joe A. Wehrmeyer, and Donald G. Rotach. June 2008. "Stereo-PIV Data Obtained behind an F-15 Model Compared to CFD Results," AIAA Paper 2008-712.

Ruyten, W. M., D. O. Williams, and F. L. Heltsley. June 1994. "Computational Flow Imaging for Planar Laser-Induced Fluorescence Applications," AIAA Paper 1994-2621.

Sellers, Marvin E. December 2005. "Advances in AEDC's Lifetime Pressure-Sensitive Paint Program," AIAA Paper 2005-7638.

Skelley, Marcus L., Tommie F. Langham, and William L. Peters. November 2004. "Integrated Test and Evaluation for the 21st Century," AIAA Paper 2004-6873.

Senge, Peter, Joe Laur, Bryan Smith, Nina Kruschwitz, and Sara Schely. 2008. *The necessary revolution: How individuals and organizations are working together to create a sustainable world*. New York: Doubleday.

von Kármán, T. December 1945. Two monographs, "Science: The Key to Air Supremacy" and "Where We Stand." In: *Towards New Horizons,* a report of the AAF Scientific Advisory Group to General of the Army, H. H. Arnold, Commanding General, Army Airfoce (AAF) 34 monographs in 12 volumes. Dayton, Ohio: Air Material Command Publications Branch, Wright Field.

Acknowledgment

The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. The views expressed in this publication are those of the author and do not reflect the official policy or position of the Department of Defense, the U.S. government, or of the U.S. Air Force. Further reproduction is authorized to meet the needs of the U.S. government.